

The inner inner core of Earth

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The solid inner core (Fig. 1) is the most remote and enigmatic part of our planet, and, next to the crust, is the smallest “official” subdivision of Earth’s interior. It was discovered in 1936 (1), and by 1972 it was established that it was solid, albeit with a very small rigidity (2–4). By 1993 it had been established that it was crystalline (5). The inner core is isolated from the rest of Earth by the low-viscosity fluid outer core, and it can rotate, nod, wobble, precess, oscillate, and even flip over, being only loosely constrained by the surrounding shells. Its existence, size, and properties constrain the temperature and mineralogy near the center of the Earth. Among its anomalous characteristics are low rigidity and viscosity (compared with other solids), bulk attenuation, extreme anisotropy, and superrotation (or deformation; refs. 5–8). From seismic velocities and cosmic abundances, we know that it is composed mainly of iron-nickel crystals, and the crystals must exhibit a large degree of common orientation. The inner core is predicted to have very high thermal and electrical conductivity, a nonspherical shape, and frequency-dependent properties; also, it may be partially molten. It may be essential for the existence of the magnetic field and for polarity reversals of this field (D. Gubbins, D. Alfe, G. Masters, D. Price, and M. Gillan, unpublished work). Freezing of the inner core and expulsion of impurities is likely responsible for powering the geodynamo. Yet, the inner core represents less than 1% of the volume of Earth, and only a few seismic waves ever reach it and return to the surface. The inner core is a small target for seismologists, and seismic waves are distorted by passing through the entire Earth before reaching it. Conditions near the center of the Earth are so extreme that both theoreticians and experimenters have difficulty in duplicating its environment. Nevertheless, there has been a recent flurry of activity about the inner core by seismologists, geochemists, dynamicists, materials scientists, and geodynamo theoreticians. Almost everything known

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or inferred about the inner core from seismology or from indirect inference is controversial. In this issue of PNAS, Ishii and Dziewoński (8) add further intrigue and complication to phenomena near the center of the Earth, and they suggest a complex history for this small object.

Planets differentiate as they accrete and gain gravitational energy. Timing of this differentiation is a long-standing goal of Earth science (9–13). Density stratification explains the locations of the crust, mantle, and core. The inner core is likely also the result of chemical stratification, although the effect of pressure on the melting point would generate a solid inner core even if it were chemically identical to the outer core. Low-density materials are excluded when solidification is slow, so the inner core may be purer and denser than the outer core. As the inner core crystallizes and the outer core cools, the material held in solution and suspension will plate out, or settle, at the core-mantle boundary and may be incorporated into the lowermost mantle. The mantle is usually treated as a chemically homogeneous layer, but this is unlikely. Denser silicates, possibly silicon- and iron-rich, also gravitate toward the lower parts of the mantle. Crustal and shallow mantle materials were sweated out of the Earth as it accreted, and some were apparently never in equilibrium with core material. The effect of pressure on physical properties implies that the mantle and core probably stratified irreversibly upon accretion, that only the outer shells of the mantle participate in surface processes such as volcanism and plate tectonics, and that only the deeper layers currently interact with the core.

The crust, upper mantle, lower mantle, core, and inner core are the textbook subdivisions of the Earth’s interior. Seismic tomography is used to map large-scale lateral variations in these major subdivisions. Higher resolution seismic techniques have been used to discover and map small-scale features at the top and bottom of the core (14–16). The classical

boundaries inside the Earth (6) were all discovered in the early part of the last century. In the 1960s, boundaries internal to the mantle were discovered at depths of 400 and 650 km and were attributed to solid-solid phase changes (17), in contrast to the others which are chemical or solidification boundaries. More recently, a probable chemical discontinuity was found deep in the mantle (16), and another one was inferred near 900 km (18). Seismic discontinuities are conventionally found by the reflection and refraction of seismic waves, but recently factors such as anisotropy, attenuation, scattering, spectral density, and statistical decorrelations have been used to find the more subtle features. The new region deep in the inner core represents a change in character of the anisotropy pattern (8) and may represent a fundamentally different phenomenon.

The long-standing controversy regarding a drawn-out (100 million years) vs. a rapid (≈ 1 million year) terrestrial accretion seems to be resolving itself in favor of the shorter time scales and a high-temperature origin. Geophysical data require rapid accretion of Earth and early formation of the core (9). Until recently, rapid accretion has been at odds with accretional theory and isotopic data, but now, these disciplines are also favoring a contracted time scale. A variety of isotopes have confirmed short time intervals between the formation of the solar system and planetary differentiation processes (10–13). This finding has bearing on the age of the inner core and its cooling history.

There are three quite different mechanisms for making a planetary core. In the homogeneous accretion hypothesis, the silicates and the metals accrete together but, as the Earth heats up, the heavy metals percolate downwards, eventually forming large dense accumulations that sink rapidly toward the center, taking the siderophile elements with them. In the heterogeneous accretion hypothesis, the refractory condensates (including iron and nickel) from a cooling nebula start to form

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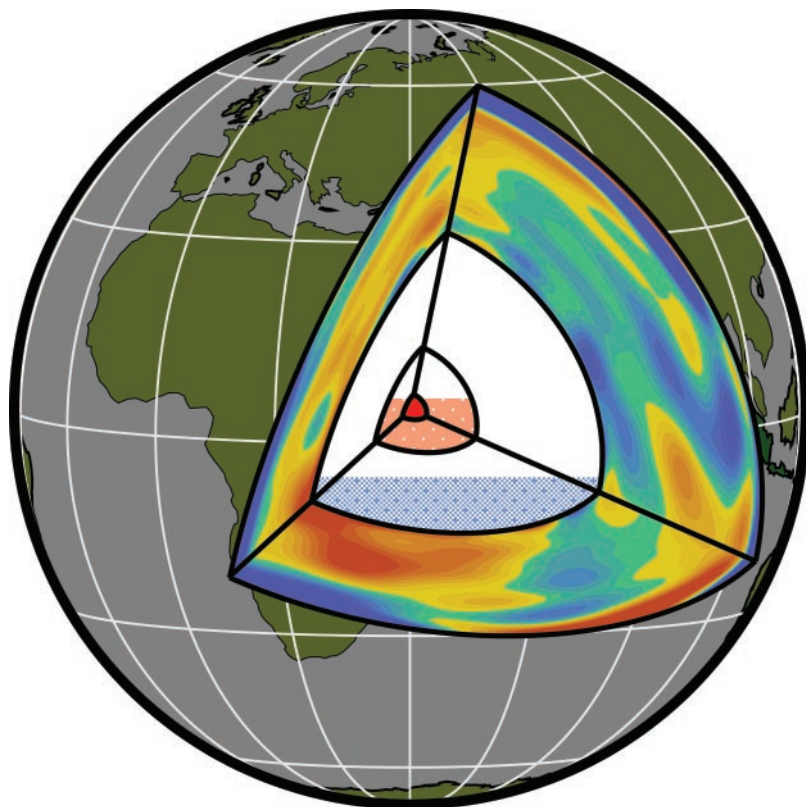


Fig. 1. View of the Earth's interior. The volumetric relation of the various regions of the core to the whole Earth is shown: outer core (pale blue) occupies 15%, the inner core (pink) occupies less than 1%, and the innermost inner core (red) constitutes only 0.01% of the Earth's volume. The Earth's core lies beneath 3,000-km thick, heterogeneous mantle (anomalies with higher than average seismic speed are shown in blue and those with lower than average speed are shown in red), making investigations of core properties challenging.

the nucleus of a planet before the bulk of the silicates and volatiles are available. The late veneer contributes low-temperature condensates and gases, including water, from the far reaches of the solar system. Finally, large late impacts can efficiently and rapidly inject their metallic cores to the center of the impacted planet and trigger additional separation of iron from the mantle. The Moon is a byproduct of one of these late impacts. The material in the core may, therefore, have multiple origins and a complex history. Other issues regarding the inner core involve its age, growth rate, density, temperature, texture, and internal energy sources (refs. 8 and 19–21, and D. Gubbins, D. Alfe, G. Masters, D. Price, and M. Gillan, unpublished work).

The outer core is usually considered to be completely molten because of its low viscosity and inability to transmit shear waves. However, it could contain more than 50% suspended crystals and still behave as a fluid. The boundary of the inner core then could represent the crossing of the geotherm with the melting curve (the conventional explanation) or a compaction boundary where the particle density of the slurry exceeds a threshold. It is

usually assumed that the outer core is homogeneous, entirely fluid, and convects turbulently. The inner core also may contain a substantial melt fraction, particularly if there is a large interval between the solidus and the liquidus. It has also been proposed that the inner core is a viscous fluid or a metallic glass (19). The new results on anisotropy make this unlikely. The low, inferred viscosity of the inner core means that it can deform and convect from the influence of tidal and rotational stresses and outer core motions as well as from internally generated stresses. The inner core is one of the few places in the interior where one might expect to see changes on a human timescale. It may exhibit semirigid differential rotation with respect to the mantle but also, and more likely, nonrigid or plastic deformation. Anisotropy is one indicator of such deformation or convection.

Crystals are anisotropic and tend to be oriented by sedimentation, freezing, recrystallization, deformation, and flow. Therefore, we expect the solid portions of the Earth to be anisotropic to the propagation of seismic waves and other material properties. Despite these expectations, seismology proceeded and flourished with

the assumption of isotropy until the 1960s. At this point, the theory of seismic anisotropy was worked out and observations verified the expectations (see references in ref. 6). Nevertheless, most seismologists ignored anisotropy until fairly recently in the progress of seismology. Not only is anisotropy a useful tool for determining composition, mineralogy, and deformation from seismology, but Earth models based on isotropy can be completely wrong. Anisotropy is not simply a small perturbation to an essentially isotropic Earth. The variation of seismic wave speeds as a function of direction can be greater than those caused by temperature and composition. In the case of the inner core (8), the penetrating seismic waves travel almost radially, so very little information is extractable, except the variation of travel time with azimuth, e.g., equatorial vs. polar paths, or with waves propagating in different directions in the equatorial plane. The size of the Fresnel zone also limits the seismic resolution of the innermost core. Fortunately, high-pressure iron crystals have a large anisotropy (21, 22); otherwise, little could be said about heterogeneity or rotation/deformation of the inner core.

The shape and fabric of the inner core are affected by gravitational forces from the mantle, electromagnetic and viscous stresses from the outer core, and rotational and tidal stresses. These stresses cause irreversible plastic flow, crystal alignment, and recrystallization. Seismic anisotropy is one result.

The inner core is subjected to a variety of external stresses involving variations in orbital and rotational parameters, tides, gravitational tugs from the mantle, viscous drag of the outer core, and electromagnetic forces. It also may generate internal stresses by thermal and chemical variations, anisotropy and cooling, and respond to these by porous flow, differential rotation, convection, and deformation and creation of material anisotropy. Anisotropy can also form by freezing of the inner core and sedimentation on its surface. Small-scale heterogeneity, for example, can melt channels or exsolution fabric and can also generate apparent anisotropy.

The conventional explanation of the formation of the solid inner core involves slow cooling and crystallization. Because the melting temperature increases with pressure, the core will solidify from the center outwards. But this effect also means that as pressure increases because of accretion, the core can pressure-freeze when the Earth reaches a critical size, unless there is a large amount of superheat. Although we know that the magnetic field is ancient and that a solid and growing inner core may be essential to its

existence, it is possible that catastrophic events such as the Moon-forming impact may have caused the inner core to reform one or more times. Initial superheat and episodic growth will possibly resolve some of the current energy problems (ref. 20, and D. Gubbins, D. Alfe, G. Masters, D. Price, and M. Gillan, unpublished work). A growing inner core is needed to power the current dynamo, but rapid cooling may

have powered the ancient dynamo (D. Gubbins, D. Alfe, G. Masters, D. Price, and M. Gillan, unpublished work). The inner core may, therefore, be much younger than the Earth. The heterogeneity and anisotropy of the inner core may help constrain its apparently complex history.

The inner core has bearing on a wide variety of geophysical, geochemical (23), magnetic field, and planetary problems.

Anisotropy is not only an important parameter bearing on core dynamics, but it also makes it possible to characterize and monitor the inner core. Anisotropy has become an indispensable tool to seismologists, rather than the bother it was once considered. And the prospect of finding differences the next time we look offers an excitement unusual in most routine mapping endeavors.

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